PB84-190537

Alternative RBC (Rotating Biological Contactor) Design - Second Order Kinetics

(U.S.) Municipal Environmental Research Lab.
Cincinnati, OH

May 84

U.S. Department of Commerce
National Technical Information Service
NTIS

PB84-190537

EPA-600/D-84-117
May 1984

AN ALTERNATIVE RBC DESIGN - SECOND ORDER KINETICS

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U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA *(Please read Instructions on the reverse before completing)*		
1. REPORT NO. EPA-600/D-84-117	2.	3. RECIPIENT'S ACCESSION NO. PB84 190537
4. TITLE AND SUBTITLE An Alternative RBC Design- Second Order Kinetics		5. REPORT DATE May 1984 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Edward J. Opatken		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Wastewater REsearch Division Municipal Environmental Research Laboratory U.S. Environmental Protection Agency Cincinnati, Ohio 45268		10. PROGRAM ELEMENT NO. 11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS Municipal Environmental Research Laboratory Office of Research and Development U.S. Environmental Protection Agency Cincinnati, OH 45268		13. TYPE OF REPORT AND PERIOD COVERED 14. SPONSORING AGENCY CODE EPA/600/14
15. SUPPLEMENTARY NOTES		

16. ABSTRACT

This paper presents an alternative method for designing rotating biological contactors (RBC) for use as a secondary treatment operation. The method uses a combination of chemical kinetics, good engineering practice, operational simplicity, and cost effectiveness to design a RBC system to treat 10 mgd having an effluent below 12 mg/L of soluble biochemical oxygen demand (sBOD).

The paper uses a step by step approach to illustrate (1) the number of RBC required, (2) the number of stages necessary to achieve the required effluent concentration, (3) the number of shafts in each stage, (4) the concentration of SBOD in each stage, (5) the effect on performance when the diurnal variation in flow ranges from 50 to 200% of design flow, and (6) when oxygen transfer governs the kinetics.

17. KEY WORDS AND DOCUMENT ANALYSIS		
a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
18. DISTRIBUTION STATEMENT Release to Public	19. SECURITY CLASS *(This Report)* Unclassified 20. SECURITY CLASS *(This page)* Unclassified	21. NO. OF PAGES 16 22. PRICE

EPA Form 2220-1 (9-73)

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An Alternative RBC Design - Second Order Kinetics

By Edward J. Opatken

For Presentation at Second International Conference on Fixed Film Processes
Washington, D.C., July 1984

INTRODUCTION

The design of rotating biological contactor (RBC) systems for municipal wastewater treatment is normally based on empirical curves developed by the various manufacturers. The user communities have relied heavily upon the RBC manufacturers to provide design assistance and to specify the number of RBC units required, as well as their arrangement into stages and trains. The users usually include a performance clause in their specifications to provide the necessary insurance that the process will produce the desired effluent quality at the specified design flow. A manufacturer's empirical curves were used to predict both interstage and final effluent quality at 10 RBC facilities, and the predicted results were considerably different from the actual results. A second order kinetic evaluation was also performed and the predicted results were in close agreement with the actual results. This paper presents an alternative design method using 2nd order kinetics and good engineering practices to specify a RBC process for secondary treatment.

The kinetics of the RBC process have been shown to follow a second order rate expression when the disappearance of soluble biochemical oxygen demand (sBOD) is correlated with time (2). This relationship can then be combined with other RBC process limitations to design RBC systems based on achieving final effluent sBOD requirements. This alternative design approach can be used to determine

- the number of shafts
- the number of stages
- the shafts in each stage
- the sBOD in each stage
- the effect on performance by diurnal variations in flow from 50 to 200% of design flow
- when oxygen transfer governs the kinetics

This paper will demonstrate the technique employed to design an RBC plant using second order kinetics and the rationale behind each step in the design process.

Plant Conditions - Assumed

Design flow = 10 MGD
Diurnal variation = 50 to 200% of design flow
Influent characteristics
TBOD = 120 mg/L
sBOD = 60 mg/L
TSS = 120 mg/L
VSS = 72 mg/L
k = 0.083 L/mg·h (from reference 2)
Requirements: Final effluent = 12 mg/L sBOD= 24 mg/L TBOD

STEP 1 Determine the number of shafts in the first stage

To avoid organic overloads and possible nuisance growths and/or shaft overloads a design limitation of 2.5 lbs sBOD/1000 sq ft (3) is a recommended condition in the Design Information Document. By applying this limitation the number of shafts required in the 1st stage can be estimated.

60 mg sBOD/L = 60 lbs/10^6 lbs x 8.3 lbs/gal x 10^7 gal/d = 5000 lbs sBOD/d

Since the standard 1st stage shafts usually have 100,000 sq ft, each shaft can handle

100,000 sq ft x 2.5 lbs/d·k sq ft = 250 lbs sBOD/d·shaft

5000 lbs sBOD/d ÷ 250 lbs sBOD/d·shaft = 20 shafts in the 1st stage

A RBC design standard set by the manufacturers is a volume to surface ratio of 0.12 gal/sq ft or a 12000 gal volume for a 100,000 sq ft RBC. Based on this design standard, the residence time in the first stage is calculated as follows:

10 MGD = 420,000 gal/h

12000 gal/shaft x 20 shafts/1st stage ÷ 420,000 gal/h = 0.57h in 1st stage= 34min

To simulate a completely mixed condition, each stage should have an assumed minimum residence time of 15 minutes. The 34 minutes of residence time calculated for the 1st stage is considerably greater than the 15 min limitation and is satisfactory for this application.

Step 2 Determine the concentration of sBOD in 1st stage

The Levenspiel equation(4) is used to determine the concentration of sBOD in the 1st stage and is represented by the following equation for 2nd order kinetics.

$$C_1 = \frac{-1 + \sqrt{1 + 4\,kt\,C_{inf}}}{2\,kt}$$

where C_1 = concentration of sBOD in the first stage
k = 2nd order reaction rate constant, 0.083 L/mg.h
t = residence time in 1st stage, 0.57h
C_{inf} = concentration of sBOD entering the 1st stage, 60 mg/L

$$C_1 = \frac{-1 + \sqrt{1 + 4\,(.083\ L/mg)(.57h)(60mg/L)}}{2\,(.083\ L/mg.h)(.57h)}$$

C_1 = 26 mg/L sBOD

Check the adequacy of oxygen transfer in the 1st stage using 40 mg O_2/h·sq ft(3) as the maximum oxygen transfer rate for a RBC containing 100,000 sq ft of plastic media and rotating at 1.6 rpm.

ΔC = 60-26 = 34 mg sBOD/L removed ≈ 34 mgO_2/L transferred

Q = 10,000,000 gal/d x 3.8 L/gal ÷ 24h/d = 1,600,000 L/h

1,600,000 L/h· ÷ 20 shafts = 80,000 L/h·shaft

34 mg sBOD/L x 80,000 L/h·shaft÷ 100,000 sq ft/shaft = 27 mg O_2/h·sq ft

27 mg O_2/h·sq ft < 40 mgO^2/h·sq ft

Therefore the 1st stage can adequately transfer the oxygen, and the system is reaction rate limited. If the oxygen transfer rate is greater than 40 mg/ O_2h·sq ft, then the concentration is determined by the oxygen transfer rate. An example of an oxygen limiting condition, that is used to determine the stage concentration, is shown on pages 6 and 7.

Step 3 Determine the number of shafts in the 2nd stage

Again applying the 2.5 lbs sBOD/1000 sq ft limitation, determine the minimum number of shafts required in the second stage.

26 mg sBOD/L ≈ 26 lbs/10^6 lbs x 8.3 lbs/gal x 10^7 gal/d = 2200 lbs sBOD/d

Therefore, the number of shafts required are:

2200 lbs sBOD/d ÷ 250 lbs sBOD/d·shaft = 8.8 ≈ 9 shafts

Another design feature endorsed by the Design Information on Rotating Biological Contactors(3) is positive flow control to each contactor for proper distribution of primary effluent to each RBC. If nine RBC are used in the 2nd stage another series of flow monitors and controls will be required to again control the flow to each of the 9 shafts to insure equal distribution. By adding another shaft, thus employing 10 shafts in the second stage, the flow from 2 RBC in the 1st stage can be directed to each RBC in the second thus eliminating the need to monitor and control the flow into the second stage. Therefore 10 contactors will be employed in the 2nd stage.

Check retention time in the 2nd stage using 10 RBC's to determine if 15 minutes residence time is provided to similate a completely mixed system.

V = 12000 gal/shaft x 10shafts = 120,000 gal

t = V/Q = 120,000 gal/420,000 gal/h = 0.29h ≈ 17min

The hydraulic residence time in the 2nd stage exceeds the 15min limitation by 2 minutes, thus 10 shafts are adequate for treatment in the 2nd stage.

Step 4 Determine the concentration of SBOD in the 2nd stage

$$C_2 = \frac{-1 + \sqrt{1 + 4(.083\ L/mg.h)(.29h)(26\ mg/L)}}{2\ (.083\ L/mg.h)(.29h)}$$

C_2 = 18 mg/L sBOD

Check adequacy of O_2 transfer in 2nd stage

ΔC = 26-18 = 8 mg/L of sBOD ≈ 8 mgO_2/L transferred

Q = 10^7 gal/d ≈ 1.6x10^6 L/h·10shafts ≈ 160,000 L/h·shaft to 2nd stage

8 mg O_2/L x 160,000 L/h·shaft ÷ 100,000 sq ft/shaft = 13 mg O_2/h·sq ft

13 mg O_2/h·sq ft < 40 mg O_2/h·sq ft

therefore the oxygen transfer is well within the capability of the 10 contactors and the 2nd stage is reaction rate limited.

Step 5 Determine the number of shafts in the third stage

Since the residence time in the second stage is 17 minutes, or only 2 minutes more than the minimum 15 minutes, then the third stage will also consist of 10 shafts which will again allow us to omit flow control equipment. The flow from each RBC in the second stage will be directed to a RBC in the third stage, thus maintaining proper flow distribution in the third stage.

Step 6 Determine the concentration in the third stage

Calculate the concentration of sBOD in the 3rd stage. Employ 10 shafts in the third stage with a residence time of 0.29h and an influent of 18 mg/L of sBOD.

$$C_3 = \frac{-1 + \sqrt{1 + 4(.083\ L/mg.h)(.29h)(18mg/L)}}{2(.083\ L/mg.h)(.29h)}$$

C_3 = 14 mg/L of sBOD

Check oxygen transfer in the 3rd stage

ΔC = 18-14 = 4 mg/L O_2 transferred

4 mg O_2/L x 160,000 L/h·shaft ÷ shaft/100,000 sq ft = 6.4 mg O_2/h·sq ft

6.4 << 40 mg O_2/h·sq ft

The capability of the contactor to transfer oxygen is more than six times its requirement in the third stage. To offset this excess oxygen transfer capability, it is proposed that the effluent from every 2 contactors in stage two be combined and directed to one contactor in stage three that is modified to contain the same volume as two standard RBC tanks. That is, a contactor with 100,000 sq ft is set in a 24000 gal tank in lieu of 2 contactors with 100,000 sq ft each set in 2 tanks which contain 12000 gallons each. This approach will reduce the contactors in stage three from 10 to 5. Savings will be achieved in capital expenditures by eliminating 5 contactors valued at $40,000 each or $200,000. Further operating savings will be obtained by cutting the power requirements in half for the third stage by eliminating 1/2 the contactors that would normally be specified and saving more than $9,000/yr in electrical power costs.

Step 7 Determine the number of shafts in stage 4

Only 5 shafts will be specified for stage 4. The same analyses that was used to specify 5 contactors in stage 3 also applies to stage 4. Each contactor sets inside a tank that contains twice the standard volume (24000 gal in lieu of 12,000 gal) to maintain an adequate mix time of 0.29h or 17 min and a controlled flow by directing the flow from each RBC in Stage 3 to an RBC in Stage 4.

Step 8 Calculate the concentration of stage 4

The calculation of the concentration in stage 4 again uses a residence time of 0.29h with an influent concentration of 14 mg/L.

$$C_4 = \frac{-1 + \sqrt{1 + 4(.083\ L/mg/h)(.29h)(14mg/L)}}{2(.083\ L/mg.h)(.29h)}$$

C_4 = 11 mg/L of sBOD

The final effluent concentration is estimated at 11 mg/L of sBOD or an assumed TBOD level of 22 mg/L. Forty shafts are required to treat 10 MGD to a level below 25 mg/L of TBOD. The arrangement consists of 20 shafts in the first stage, followed by 10 shafts in the second stage and 5 shafts each in the 3rd and 4th stages. However the tankage in the 3rd and 4th stages equal the tankage in the 2nd stage as well as the same hydraulic residence time.

Diurnal Variation

The effect of changing conditions, such as flow can be analyzed by the second order rate expression or by oxygen transfer if this factor becomes the limiting condition. We assumed an increase in flow of about twice the design flow for diurnal variation and, vise versa, we assumed a drop in the flow of 1/2 design flow because of diurnal variation. This differential increase or decrease in flow can be taken into consideration by a kinetic analyses. The overall daily effluent is calculated to determine if the final effluent quality is being compromised by relying upon average conditions to specify equipment requirements without any consideration for diurnal variations.

The analysis for determining the effect of a diurnal flow variation between 50 and 200% of design flow is based on a second order rate expression to calculate the effluent quality.

With a 200% increase in flow, the reaction time will be reduced to 50% of the residence time at design flow. Conversely the reduction of flow at 50% of design will double the residence time in each stage. The diurnal effects of flow variation on residence time are shown in table 1.

Table 1. Effect of Diurnal Flow on Residence Time

Time in Stage	Design flow	50% Design	200% Design
t_1,h	.57	1.14	.28
t_2,h	.28	.57	.14
t_3,h	.28	.57	.14
t_4,h	.28	.57	.14

The reaction times are then inserted into the 2nd order rate expression to determine the concentrations in each of the 4 stages for both low flow and high flow conditions. The reaction rate constant remains at 0.083 L/mg·h and the initial concentration is assumed at the same level, 60 mg/L of sBOD.

An example for determining the concentration of sBOD in stage 1 with a flow of 200% of design flow is shown below

$$C_1 = \frac{-1 + \sqrt{1 + 4\,ktC_o}}{2\,kt}$$

where $k = 0.083$ L/mg·h
$C_0 = 60$ mg sBOD/L
$t = .28$h at 200% design flow

$$C_1 = \frac{-1 + \sqrt{1 + 4(.083)(.28)(60)}}{2\,(.083)(.28)}$$

$C_1 = 34$ mg/L of sBOD

Past work has shown that the RBC are capable of tranferring a maximum of 40 mg O_2/h·sq ft. This limitation on oxygen transfer needs to be assessed to insure that the process remains only kinetically limited during the periods of high diurnal flow.

An example of the calculation to determine whether the process is kinetically limited or oxygen transfer limited is again illustrated below:

(60 mg/L - 34 mg/L) = 26 mg/L of sBOD removed or O_2 transferred

26 mg/L x 3.8 L/gal x 12000 gal/0.28h ÷ 100,000 sq ft = 42 mgO_2/h·sq ft

Since the oxygen requirement is 42 mg/h·sq ft and a RBC can only transfer 40 mg O_2/h·sq ft, the process is assumed to be oxygen transfer limited and the concentration in the 1st stage is calculated as follows:

40 mg/h·sq ft x 100,000 sq ft x.28h/12000 gal x gal/3.8 L = 24 mg/L of O_2

60 mg/L - 24 mg/L = 36 mg/L of sBOD which is the estimated concentration in the 1st stage which is controlled by oxygen transfer.

Using the concentration in stage 1 as the influent to stage 2, calculate the concentration in stage 2 using the 2nd order rate equation.

$$C_2 = \frac{-1 + \sqrt{1 + 4kt_2C_1}}{2kt_2}$$

$$C_2 = \frac{-1 + \sqrt{1 + 4(.083)(.14)(36)}}{2(.083)(.14)}$$

C_2 = 27 mg/L

ΔC = 36-27 = 9 mg/L of sBOD removed or O_2 transferred

Since the residence time in stage 2 is only 1/2 the residence time in stage 1, a recheck of the O_2 transfer limitation is required.

9 mgO_2/L x 3.8 L/gal x 12000 gal/.14h ÷ 100,000 sq ft = 29 mgO_2/h·sq ft

which is below the 40 mg O_2/h·sq ft that the contactor is capable of transferring; therefore the second stage is reaction rate limited and the concentration is calculated by the second order rate expression.

Since the residence time in stages 3 and 4 equals the residence time in stage 2 and the concentration in stage 2 is greater than the concentrations in stages 3 and 4, the oxygen trasfer rate or the sBOD removal rate in stages 3 and 4 will be less than stage 2 and will be chemical reaction rate limited. The concentrations for stages 3 and 4 can be calculated by the 2nd order rate expression and it will not be necessary to check for oxygen transfer limitation because the influent concentration in stages 3 and 4 are less than stage 2.

The results are shown in Table 2 for the 50% and 200% of design flow and also for the combined analyses involving both O_2 transfer and kinetics as the limiting factor.

Table 2 Concentrations at Diurnal Flow Conditions

	Design	50% Design	200% Design (kinetically limited)	200% Design* O_2 & kinetically limited
C_0, mg/L	60	60	60	60
C_1, mg/L	26	20	34	36
C_2, mg/L	18	12	26	27
C_3, mg/L	14	8.5	21	22
C_4, mg/L	11	6.5	17	18

* Predicted concentrations

If these results are weighted over 24 hours, the mean sBOD of final effluent is conservatively estimated by assuming that both high and low flows occurs for 6 hours and design flow occurs for 12 hours.

$$C_{eff} = \frac{(12 \times 11) + (6 \times 6.5) + (6 \times 18)}{24} = 12 \text{ mg/L sBOD} \approx 24 \text{ mg/L of TBOD}$$

The overall effect of diurnal variation is to increase the final effluent quality from 11 to 12 mg sBOD/L or from 22 to 24 mg TBOD/L which remains below the desired level of 25 mg/L of TBOD.

Summary

The 2nd order design method specified a total of 40 contactors arranged into 20 contactors in the 1st stage, followed by 10 contactors in the 2nd stage and 5 contactors with twice the hydraulic volume in the 3rd & 4th stage.

The 2nd order approach for designing RBC systems employs chemical kinetics good engineering practice and operational simplicity to design a cost effective RBC process.

- the kinetics governed the number of contactors and stages
- the organic loading limitation governed the number of contactors in the first stage
- good engineering practice was applied by designing below the recommended organic loading of 2.5 lbs/d·k sq ft to avoid nuisance growths; and by employing a minimum 15min hydraulic residence time in each stage to achieve completely mixed conditions
- operational simplicity was applied by using controlled flows into the first stage and then specifying the number of contactors in succeeding stages to insure equal hydraulic residence time without using flow monitors and controllers.
- cost effectiveness was achieved by removing 1/2 the contactors in the final 2 stages, while maintaining the tankage and hydraulic residence time to achieve the required reaction kinetics.

MANUFACTURERS DESIGN METHOD

The design of the RBC facility using second order kinetics can be compared with the method used by Envirex. The Envirex (Autotrol) Design Manual(5) was

used to design a RBC facility using the identical plant conditions that were specified for the illustrative example using second order kinetics.

The design curve displayed in Figure C-1b showing the effluent soluble BOD at various hydraulic loadings was used to determine the surface area requirements. To achieve a sBOD level of 12 mg/L with an influent containing 60 mg/L requires a hydraulic loading below 3.5 gpd/sq ft.

10,000,000 gal/d ÷ 3.5 gal/d·sq ft = 2,900,000 sq ft

Since there are 100,000 sq ft per contactor, the total number of contactors required to treat 10 MGD is obtained as follows:

2,900,000 sq ft ÷ 100,000 sq ft/contactor = 29 contactors

The shafts required in the 1st stage are determined by using Autotrol's recommended loading rate of 4 lbs sBOD/d·k sq ft(5)

60 mg/L ≈ 60 lbs sBOD/10^6 lbs x 8.3 lbs/gal x 10^6 gal/d = 5000 lbs/d

5000 lbs/d ÷ 4 lbs/d·k sq ft = 1,250 k sq ft ≈ 13 contactors

Table C-2 in the Autotrol Design Manual recommends 2 or 3 stages when the design effluent lies between 10 and 15 mg/L of sBOD.

The use of 13 shafts in the first stage leaves 16 shafts for the following 2 stages. The 2nd stage limitation specified by the Autotrol Design Manual required that the surface area be at least 50% of the surface area of the 1st stage. This condition is met if the remaining 16 contactors are equally divided between the 2nd and 3rd stage.

Overall the Autotrol Design Manual would specify 13 contactors in the 1st stage followed by 8 contactors each in the 2nd & 3rd stages.

Diurnal Variation

The daily effluent quality that must be produced by the RBC process is governed by the diurnal variation that was specified for this illustractive example. The low flow condition produces an effluent with a concentration that is below the lower limit on the design curve in Figure C-1B. The lowest concentration is 5 mg/L and this value is used to calculate the daily effluent quality.

At 200% of design flow the hydraulic loading rises to 7.0 gal/d·sq ft. The effluent concentration at this hydraulic loading is beyond the limits of the design curve displayed in C-1B. The maximum hydraulic loading that can be used with an influent of 60 mg/L is 5.0 gal/d·sq ft. At this hydraulic loading the effluent concentration is 25 mg/L. Assuming the hydraulic loading rate at 200% of design flow is 5.0 gal/d·sq ft, then the hydraulic loading at design flow is 2.5 gal/d·sq ft. At 2.5 gal/d·sq ft the effluent concentration is 7 mg/L. The hydraulic loading at low flow conditions is 1.2 gal/d·sq ft; the predicted effluent remains at the minimum level of 5 mg/L which coresponds to the lower limit displayed in curve C-1B.

The daily effluent quality is calculated by assuming 6 hours of operation at 50% and 200% of design flow and 12 hours at design flow. The daily effluent quality based on these conditions is calculated as follows:

C_{eff} = (6h x 5 mg/L) + (12h x 7 mg/L) + (6h x 25 mg/L)/24h = 11 mg/L

The surface area, or the number of contactors required to achieve this level of treatment is then calculated by using the hydraulic loading of 2.5 gal/d·sq ft at design flow.

10,000,000 gal/d ÷ 2.5 gal/d·sq ft = 4,000,000 sq ft ≈ 40 contactors

Forty contactors are required to achieve a final effluent quality of 11 mg/L of sBOD with diurnal flow variation that range from 50 to 200% of design flow by using the Autotrol Design Manual and keeping the conditions within the limits shown on the design curve (Figure C-1B). The results on the total number of contactors yield the same outcome regardless if 2nd order kinetics or the Autotrol Design Manual is used to specify the number of contactors.

The 1st stage surface area requirements can be estimated by using the curve displayed in Figure C-2B of the Design Manual. The overall soluble BOD loading is calculated as follows:

60 mg/L ≈ 60 lbs/10^6 lbs x 8.3/gal x 10^6 gal/d ÷ 4,000k sq ft = 1.2 lbsBOD/d·k sq ft

A minimum of 30% of the total media area is needed in the 1st stage or a least 12 contactors. Table C-2 in the Autotrol Design Manual recommended that 2 or 3 stages be used to achieve a final effluent between 10 and 15 mg/L. In this case two stages would be specified with 20 shafts/stage to provide postive flow control and keep the number of contactors at a minimum.

A comparison of two design methods is displayed in Table 3.

Table 3 Comparison of Design Methods

	Second Order	Envirex
Flow, mgd	10	10
Diurnal flow variation, %	50-200	50-200
Influent sBOD, mg/L	60	60
Contactors	40	40
Stages, no	4	2
Hydraulic loading, gpd/sf	2.5	2.5
1st stage organic loading, lbs/d·ksf	2.5	2.5
Effluent at design flow, mg/L	11	7
Effluent at 50% flow, mg/L	6.5	<5
Effluent at 200% flow, mg/L	18	25
Daily effluent, mg/L	12	11
Overall residence time, h (min)	1.44(86)	1.44(86)
1st stage residence time, h (min)	.57(34)	.57(34)
2nd stage residence time, h (min)	.29(17)	.57(34)
3rd stage residence time, h (min)	.29(17)	--
4th stage residence time, h (min)	.29(17)	--
Average flow operation		
Influent, mg/L	60	60
1st stage concentration, mg/L	26	25
2nd stage concentration, mg/L	18	7
3rd stage concentration, mg/L	14	
4th stage concentration, mg/L	11	
50% flow operation		
Influent	60	60
1st stage concentration, mg/L	20	7
2nd stage concentration, mg/L	12	<5
3rd stage concentration, mg/L	8.5	
4th stage concentration, mg/L	6.5	
200% flow operation		
Influent	60	60
1st stage concentration, mg/L	36	indeterminate
2nd stage concentration, mg/L	27	25
3rd stage concentration, mg/L	22	
4th stage concentration, mg/L	18	

Summary

The 2nd order kinetic design method was used to illustrate a design approach for specifying and arranging RBC. It provides the designer with a comprehensive analyses of the RBC process. By analyzing the average conditions and the expected overloads, such as the effect of effluent quality by diurnal flow variation, the designer has a better understanding of the capability of the process. These analyses can then be incorporated into the operating document which will enable operators to better understand the limits of the process and to seek remedies whenever conditions fall outside the limits.

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